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Spacecraft Power Management and Distribution

Advanced Power Electronics Components

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All aerospace systems require Power Management and Distribution (PMAD) between energy source and loads. All power electronics and control circuits for PMAD systems require electrical components for switching, rectification, energy storage, voltage/current transformation, filtering regulation, protection, and isolation. In order to increase the power density, efficiency, operating temperature, radiation resistance, and reliability of PMAD systems requires advances in power electronics materials and component technology. The primary means to develop advanced power electronics components is to develop new and/or significantly improved materials for capacitors, magnetic components (transformers and inductor), and semiconductor switches and diodes.

The specific benefits of developing advanced power electronics component technology are:

1. Higher operating frequency components give increased PMAD power density by reducing mass and volume of the passive components (transformers, inductors, and filter capacitors).
2. Higher operating temperature components give reduced cooling requirements and thus reduce complexity, size, and mass of the thermal transport system and radiators.
3. Higher efficiency components not only give reduced cooling requirements but also give reduced power generation and storage needs for a given output power.
4. Higher radiation resistant components give reduced mass and volume of shielding materials.
5. Higher voltage components give higher power systems and give reduced cable mass.

This paper will give a description and status of the Advanced Power Electronics Materials and Components Technology program being conducted by the NASA Glenn Research Center for future aerospace power applications. The focus of this research program is on the following:

1. New and/or significantly improved dielectric materials for the development of power capacitors with increased volumetric efficiency, energy density, and operating temperature. Materials being investigated include nanocrystalline and composite ceramic dielectrics and diamond-like-carbon films.
2. New and/or significantly improved high frequency, high temperature, low loss soft magnetic materials for the development of transformers/inductors with increased power/energy density, electrical efficiency, and operating temperature. Materials being investigated include nanocrystalline and nanocomposite soft magnetic materials.
3. Packaged high temperature, high power density, high voltage, and low loss SiC diodes and switches. Development of high quality 4H- and 6H- SiC atomically smooth

substrates to significantly improve device performance is a major emphasis of the SiC materials program.

4. Demonstration of high temperature (>200C) circuits using the components developed above.

ADVANCED POWER ELECTRONICS COMPONENTS

Presentation to

POWER SYSTEMS CONFERENCE

RENO, NEVADA

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Outline

- INTRODUCTION
- SOFT MAGNETIC MATERIALS
- DIELECTRICS AND CAPACITORS
- WIDE BANDGAP SEMICONDUCTOR MATERIALS & DEVICES
- CONCLUSIONS

Introduction

- **Motivation for doing Advanced Electrical Materials and Component Development**
  - What are the benefits?
- **Rationale for selecting the magnetic, dielectric, and semiconductor materials investigated**
  - What prior theoretical or experimental research justifies the selections?
- **Complete technical details of some research investigations can not be given**
  - Proprietary data (R&D Contracts)
  - Unpublished data (University Grants)
  - Potential flight mission data

Introduction

- **Programmatic**
  - Glenn Research Center has the responsibility to develop Advanced Electrical Materials and Component Technology (AEMCT) for future aerospace power systems
    - AEMCT is an element of Energetics project of NASA's Enabling Concepts and Technology Program
    - Energetics is a balanced program directed to provide critical technologies to meet the needs of NASA and the Nation

Introduction

- **Motivation**
  - All Aerospace missions (spacecraft, launch vehicles, planetary surface exploration, aircraft) require electrical Power Management and Distribution (PMAD) between energy source and load.
  - Advanced electrical components needed to advance PMAD state-of-the-art
    - Semiconductor switches (MOSFETs, IGBTs, thyristors, etc.)
    - Semiconductor diodes (pn junction, Schottky)
    - Transformers and Inductors
    - Capacitors
  - New and improved electrical/electronic materials needed to develop advanced electrical components
    - Magnetic
    - Dielectric
    - Insulating
    - Semiconductor
    - Solders and Contact Materials

Introduction

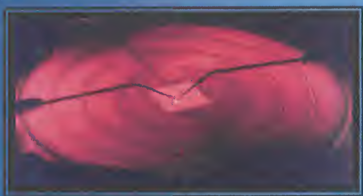
- **Benefits of Advanced Electrical Components**
  - Higher operating frequency components give
    - Increased PMAD power density by reducing mass/volume of transformers, inductors, and capacitors
  - Higher operating temperature components give
    - Reduced cooling requirements and thus reduce complexity, size, and mass of thermal transport system and radiators
  - Higher efficiency components give
    - Reduced cooling requirements
    - Reduced power generation and storage needs for a given output power
  - Higher radiation resistant components give
    - Reduced mass and volume of shielding materials
  - Higher voltage components give
    - Higher power systems
    - Reduced power transmission cable mass

Introduction

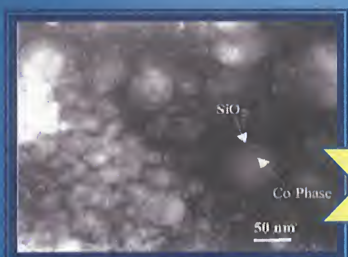
- **Power System Benefits**
  - Increased Payload Capability
  - Decreased Spacecraft Mass/Volume/Cost
  - Increased Design Flexibility
  - Increased Reliability

Roadmap for Advanced Components Technology Development

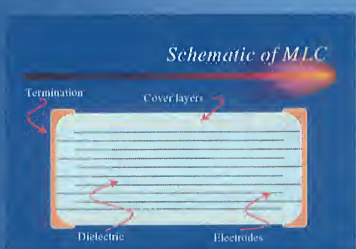
New Materials



Advanced Semiconductors

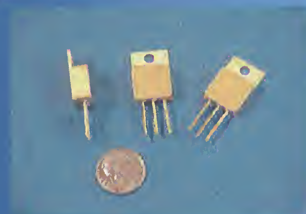


Advanced Magnetic Materials



Advanced Dielectrics

Advanced Components



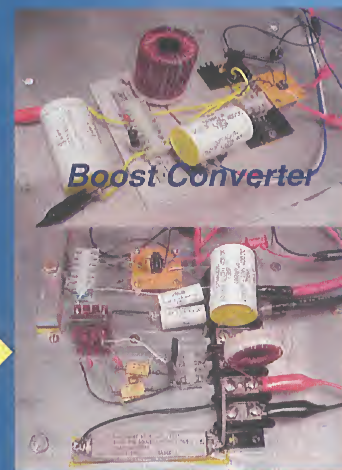
SiC Switches and diodes

High Temperature Transformers

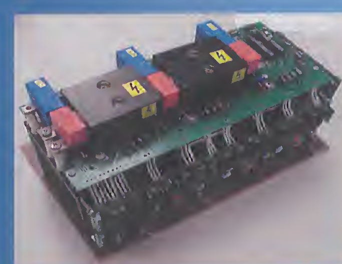
High Temperature Capacitors

Power Electronics

DC-DC Converters



Half-Bridge Converter



Inverter Modules

Mission Applications

Advanced Launch Vehicles

Advanced Aerospace

Large Power Systems for Deep Space Missions

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- **SOFT MAGNETIC MATERIALS**

Soft Magnetic Materials

Desired soft magnetic material properties		
High Power/Energy Density	**High Temperature**	**High Efficiency**
• High Saturation Flux Density, B_s • Flat B_s vs. T curve over wide temperature range	• High Curie Temperature • High Thermal Conductivity • Stable Characteristics under Temperature Cycling • Stable Characteristics at High Temperature • Predictive Aging Effects	• Low Coercive Force • High Permeability at Operating Flux Density • Low Core Loss at Operating Frequency and Temperature

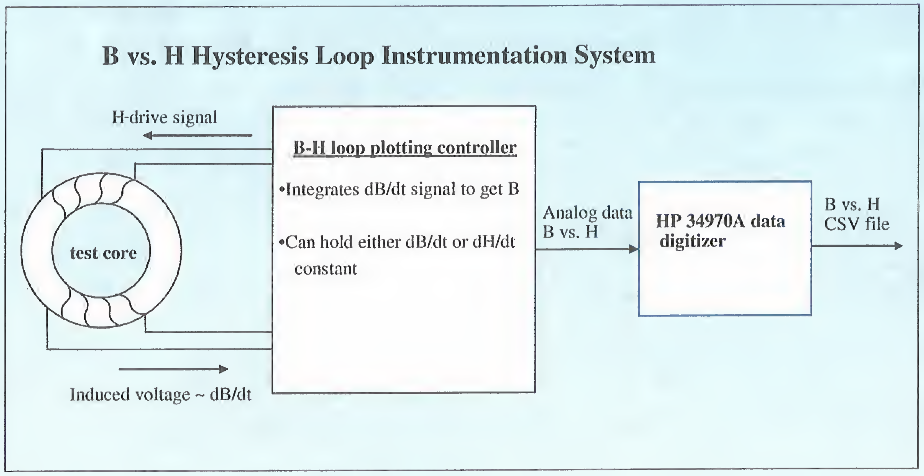
Soft Magnetic Materials

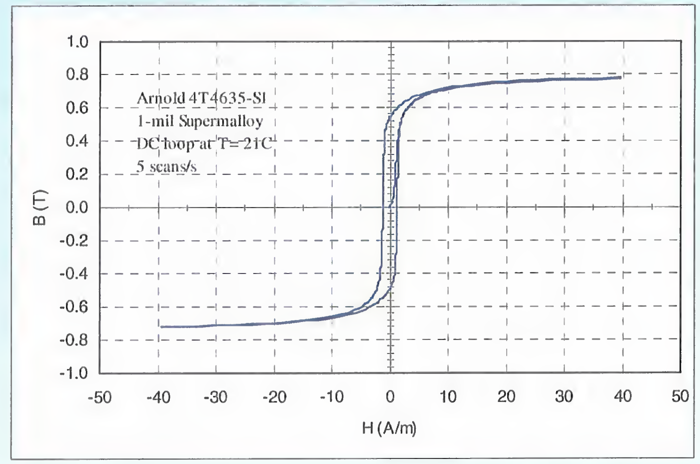
- **Core Loss Major Consideration in Power Magnetics**
  - Core loss is power dissipated in magnetic material due to hysteresis, eddy current and anomalous (excess eddy current) losses
  - Core loss is a function of
    - Material type
    - Lamination or Tape Thickness
    - Peak Operating Flux Density
    - Frequency
    - Temperature
    - Type of Excitation (Voltage or Current)
    - Excitation Waveform (Sine, Square, etc.)

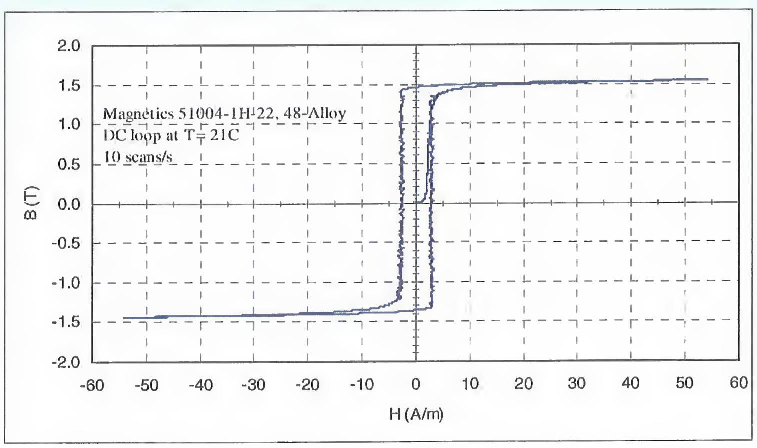
Soft Magnetic Materials

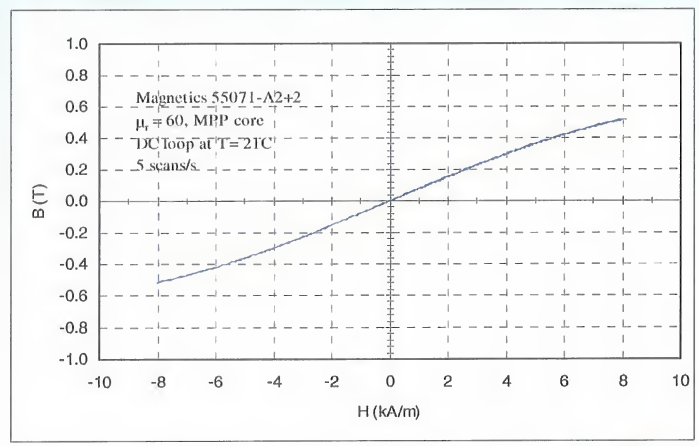
- **In-House Research**
  - Unique core loss, static and dynamic B-H hysteresis loop measurement system developed for transformer (low Q) and inductor (high Q) magnetic materials characterization
    - Temperature Range --- -150 C to 300 C
    - Frequency Range --- DC to 1 MHz
    - Flux Density --- Up to B_{SAT}
    - Voltage Excitation Waveforms --- Sine and Square
  - Extensive experimental data base developed and published on B-H loop and core loss characteristics
    - Polycrystalline alloys (NiFe, CoFe, SiFe)
    - Amorphous alloys (Fe-based, Co-based)
    - Nanocrystalline (Fe-based)
    - Power Ferrites (MnZn)

DC HYSTERESIS PLOTTER









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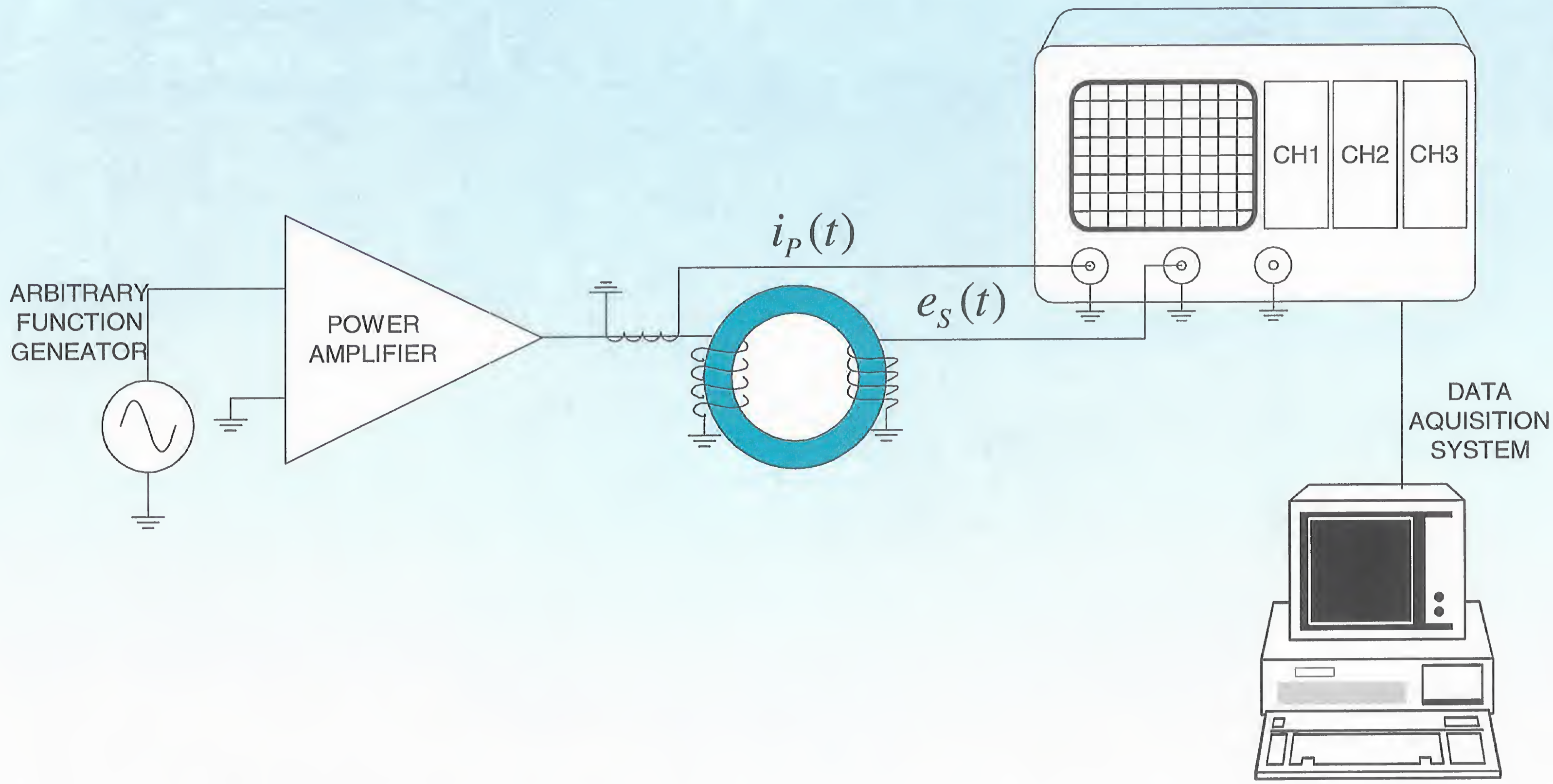
Core Loss and Dynamic B-H Loop Measurement System



MATERIALS PREVIOUSLY CHARACTERIZED UNDER SINE WAVE VOLTAGE EXCITATION

POLYCRYSTALLINE ALLOYS

TEST CONDITIONS

MATERIAL	COMPOSITION	FREQUENCIES (kHz)	TEMPERATURES (C)
SUPERMALLOY	79% Ni, 17% Fe, 4% Mo	1, 5, 10, 20, 50	23, 50, 100, 150, 200, 250, 300
ORTHONOL (SQ)	50% Ni, 50% Fe	1, 5, 10, 20, 50	23, 50, 100, 150, 200, 250, 300
48 ALLOY (RD)	50% Ni, 50% Fe	1, 5, 10, 20, 50	23, 50, 100, 150, 200, 250, 300
MAGNESIL	3% Si, 97% Fe	0.1, 0.4, 1, 2.5, 5, 7.5, 10	23, 50, 100, 150, 200, 250, 300
SUPERMENDUR	49% Co, 49% Fe, 2% V	0.1, 0.4, 1, 2.5, 5, 7.5, 10	23, 50, 100, 150, 200, 250, 300

AMORPHOUS MATERIALS

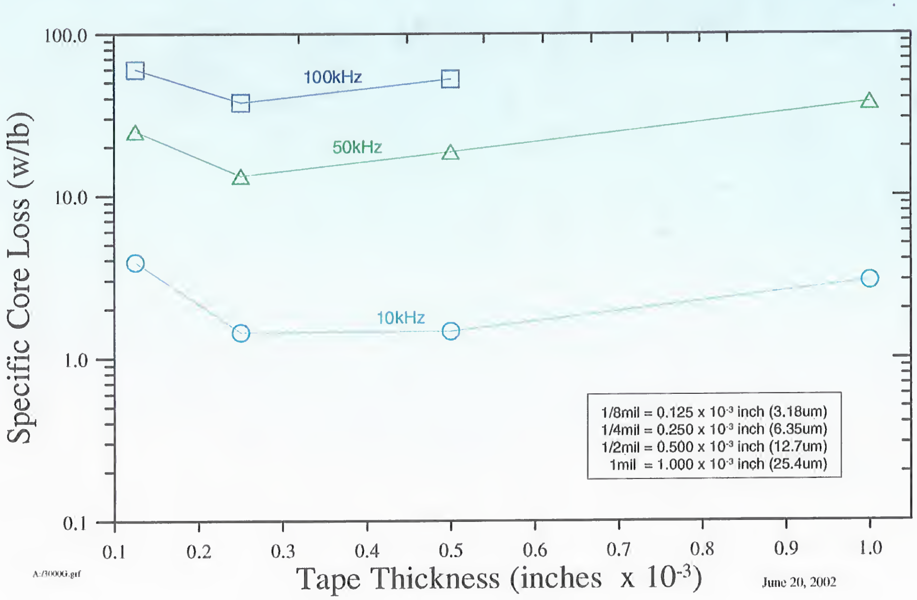
METGLAS 2605SC	$Fe_{81}\ B_{13.5}\ Si_{3.5}\ C_2$	1, 5, 10, 20, 50	23, 50, 100, 150, 200, 250, 300
METGLAS 2605S-3A	$Fe_{77}\ B_{165}\ Cri_2\ Si_5$	1, 5, 10, 20, 50	23, 50, 100, 150, 200, 250, 300
VACUUMSCHMELTZE 6025F	$(Co\ FeMo)_{73}(SiB)_{27}$	50, 100, 300, 400, 500	-150 TO +150
VACUUMSCHMELTZE 6035F	$(Co\ FeMnMo)_{77}(SiB)_{23}$	50, 100, 300, 400, 500	-150 TO +150

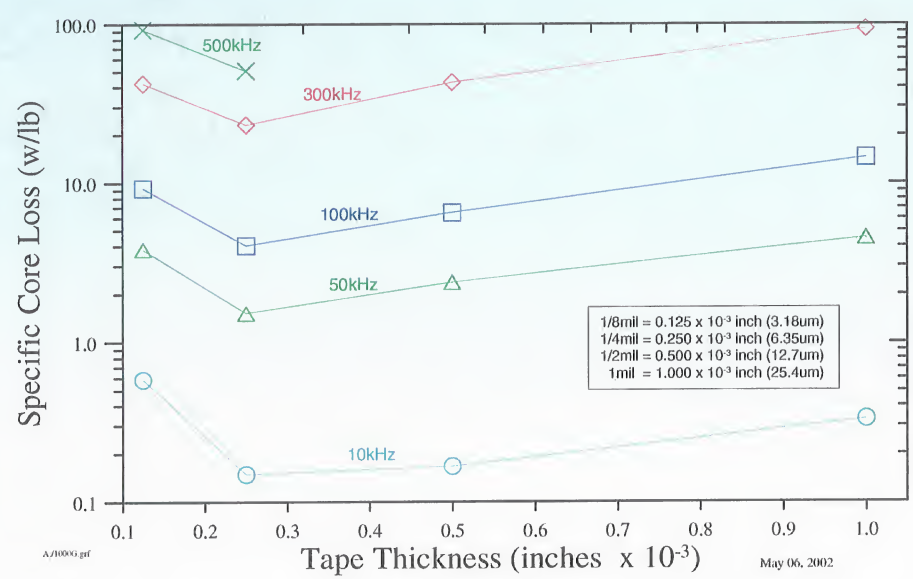
NANOCRYSTALLINE MATERIALS

VACUUMSCHMELTZE 500F	?	50, 100, 300, 400, 500	-150 TO +150

Specific Core Loss Vs Tape Thickness and Frequency

Solid Line: Supermalloy 1, 1/2, 1/4-mil Thick Tape
Dashed line: Square Permalloy 80, 1/8-mil Thick Tape





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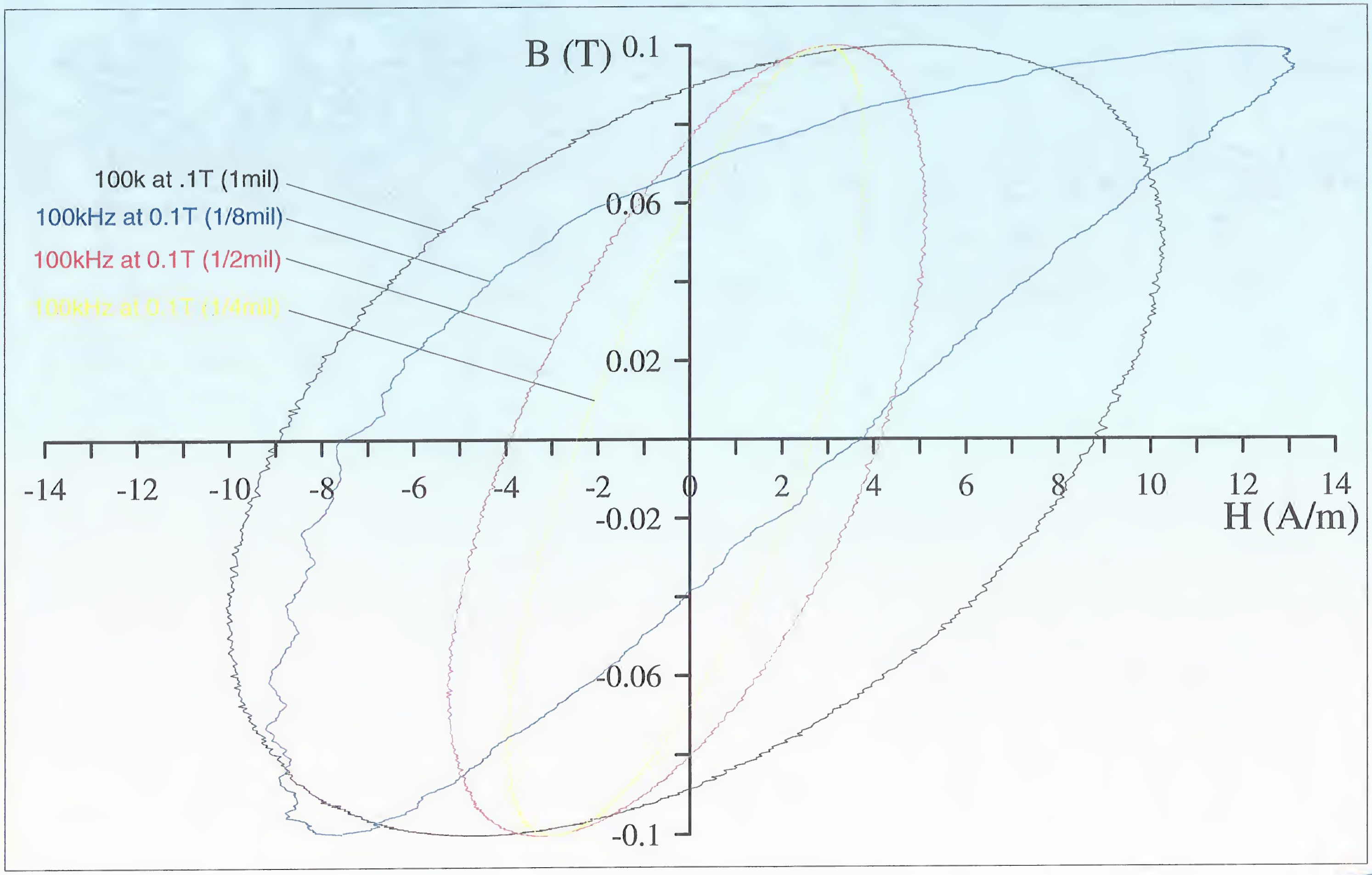
Dynamic B-H Loop at f=100kHz

1, 1/2, and 1/4-mil thick tapes are Supermalloy

1/8-mil Thick Tape is Square Permalloy 80



Soft Magnetic Materials

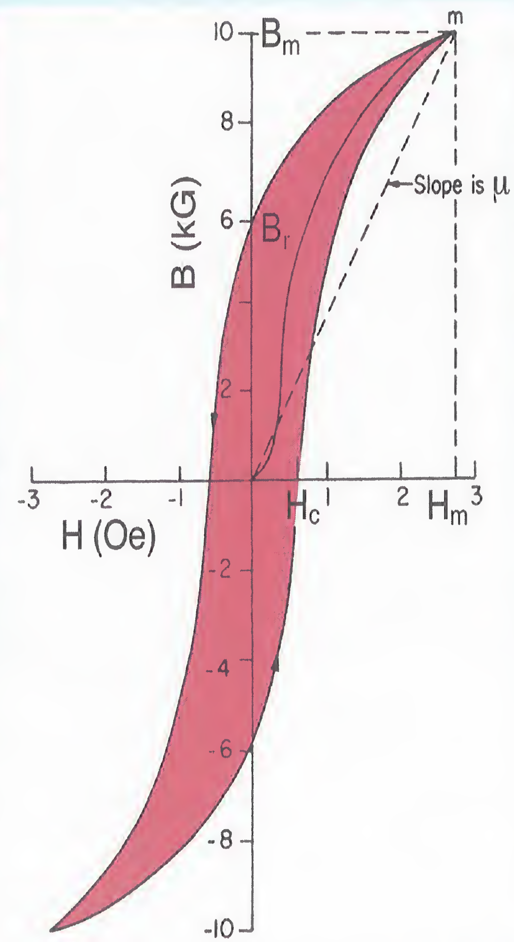
Comparison of Amorphous, Nanocrystalline, Polycrystalline, and Power Ferrite Losses					
Specific Core Loss (w/lb) @ 100 kHz and 25 C					
Max Flux Density	**6025F** (Amorphous)	**500F** (Nanocrystalline)	**Supermalloy** (Polycrystalline)	**Supermalloy** (Polycrystalline)	**MN8CX** (Ferrite)
(T)	(23 μm Tape)	(23 μm Tape)	(25.4 μm Tape)	(6.35 μm Tape)	(Solid)
0.1	2.9	4.0	14.6	4.1	4.8
0.2	11.7	15.9	54.4	17.0	33.7
0.3	27.9	35.7	119	37.9	98.0

Soft Magnetic Materials

Comparison of Amorphous, Nanocrystalline, Polycrystalline, and Power Ferrite Losses					
Specific Core Loss (w/lb) @ 0.1 T and 25 C					
Frequency	**6025F** (Amorphous)	**500F** (Nanocrystalline)	**Supermalloy** (Polycrystalline)	**Supermalloy** (Polycrystalline)	**MN8CX** (Ferrite)
(kHz)	(23 μm Tape)	(23 μm Tape)	(25.4 μm Tape)	(6.35 μm Tape)	(Solid)
100	2.9	4.0	14.6	4.1	4.8
200	9.9	14.8	NO DATA	NO DATA	14.6
300	19.9	30.6	94.2	22.0	32.2

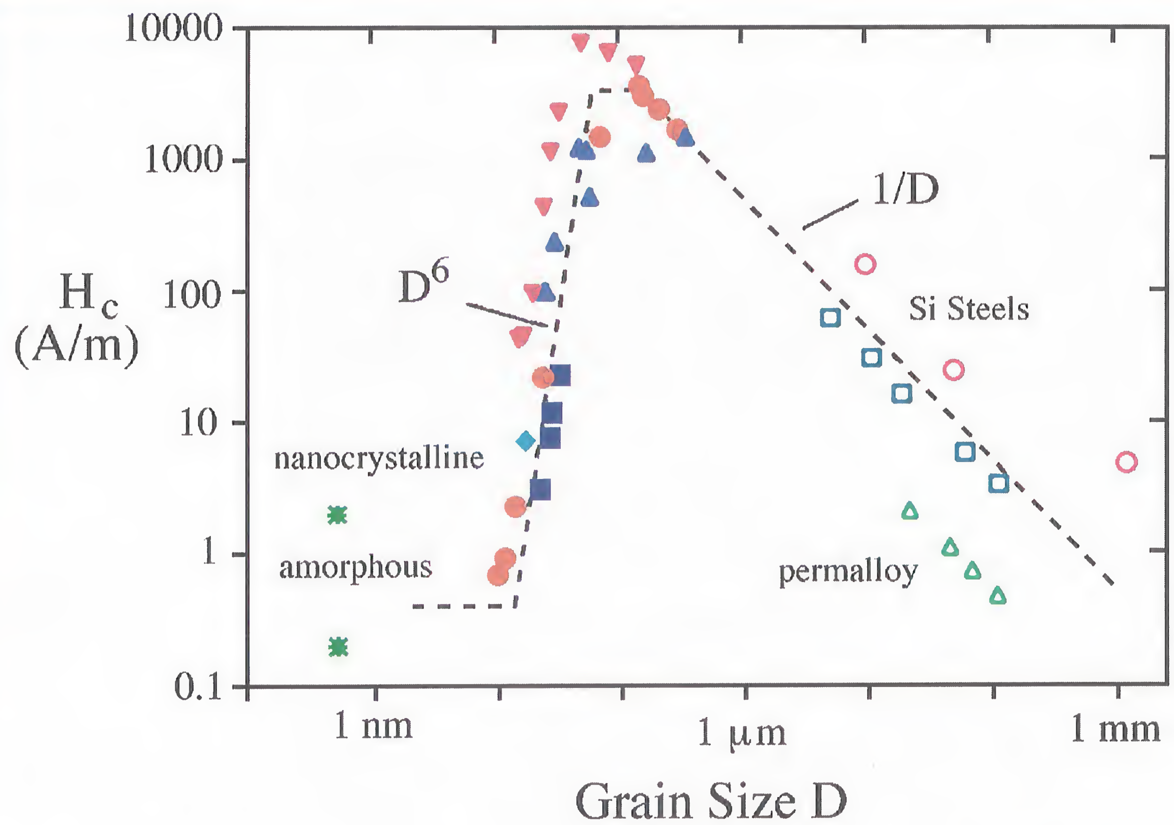
Soft Magnetic Materials

- Research focused on the identification, exploration, characterization, and evaluation of soft nanocrystalline and nanocomposite magnetic materials
  - Nanocrystalline materials produced by partial re-crystallization of an amorphous alloy to give a two-phase structure
    - Crystalline grains of 10-20 nm embedded in amorphous intergranular phase
  - Nanocomposite materials fabricated by compaction of insulated magnetic nanoparticles of dimensions less than 50 nm



Soft Magnetic Materials

- **Why Nanocrystalline and Nanocomposite Magnetic Alloys?**
  - Offer opportunity to develop new and improved magnetic alloys
    - High Flux Density
    - High/Wide Temperature
    - High Frequency
    - Low dc Coercivity
    - Low Loss



From: G.Herzer, Journal of Magnetism and Magnetic Materials 112 (1992), Figure 2, p. 259, North-Holland

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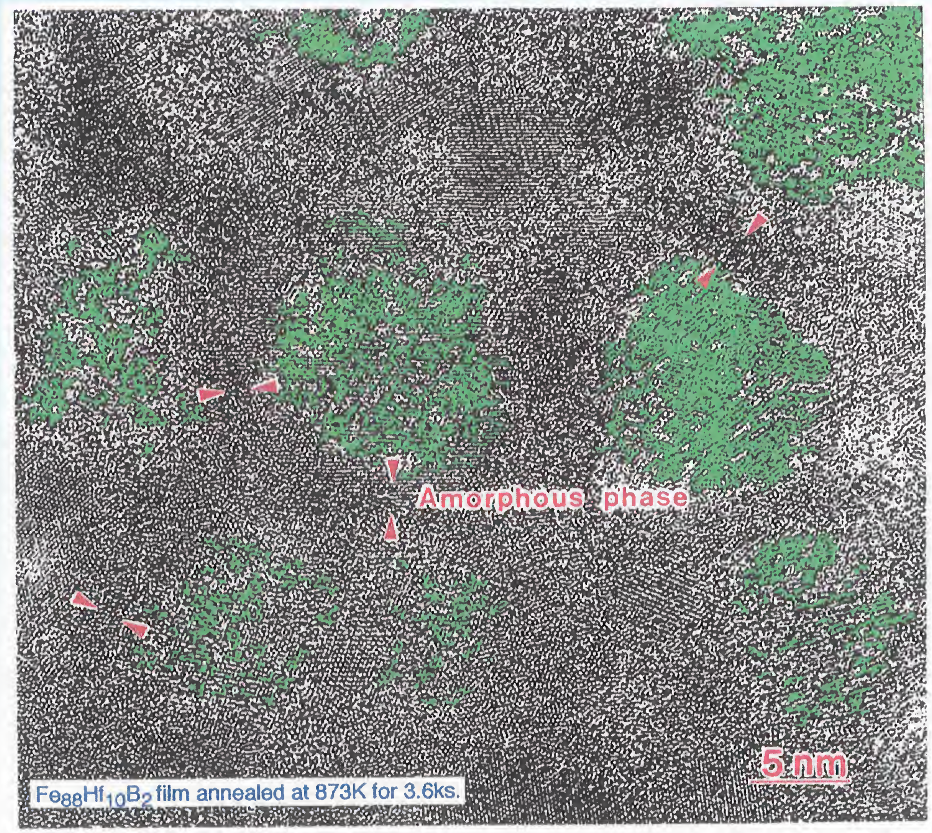
Soft Magnetic Materials

- **Nanocrystalline Vs. Nanocomposite Magnetic Alloys**
  - Nanocrystalline Magnetic Alloys
    - High resistivity compared to polycrystalline alloys
    - Fabrication process starts with amorphous precursor tape and final product is a tape after partial crystallization.
      - Usage mostly restricted to tape wound cores

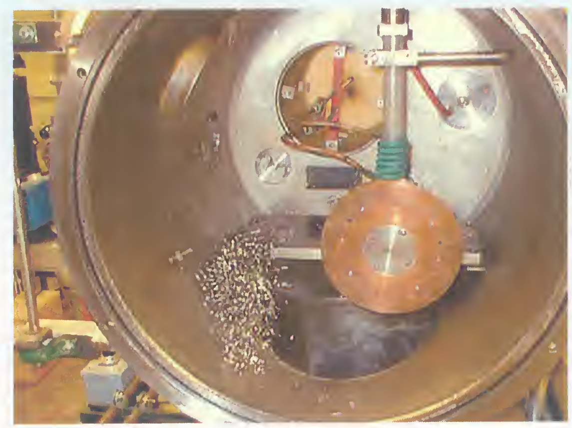


(A. Inoue, etal, *Mat. Trans.* **36** (1995), 924-38)

- **Nanocrystalline grains (green)**
  - **15-20 nm diameter**
- **Amorphous phase**
  - **between grains**

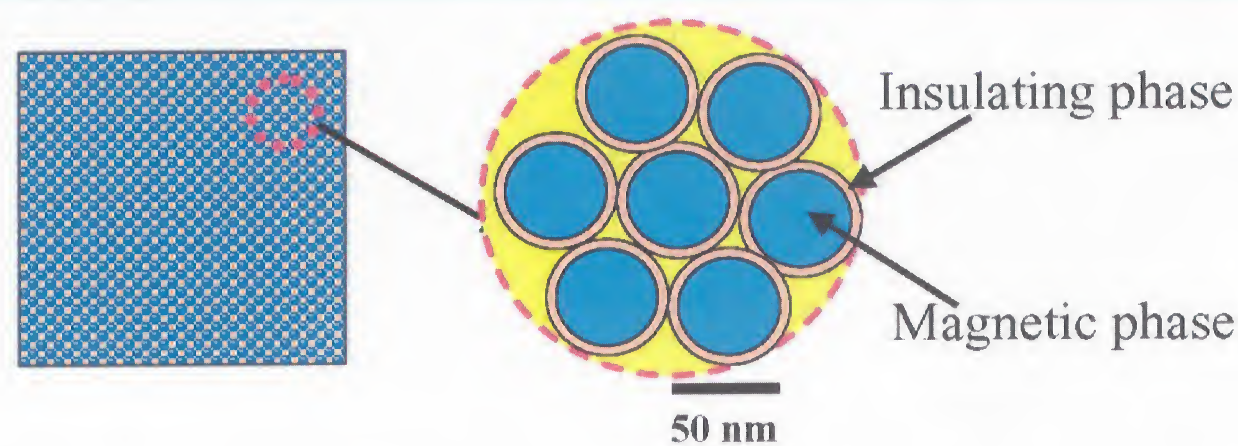
Soft Magnetic Materials

- **Sponsored Nanocrystalline Research**
  - Collaborative effort with Carnegie Mellon University (CMU)
    - PI supported under NASA's Graduate Student Research Program
  - Objective: Develop high temperature (>300C), high frequency, low core loss, high saturation induction nanocrystalline alloy
    - Investigation of HITPERM compositional variants and annealing techniques primary research effort
    - HITPERM is a new class of nanocrystalline magnetic alloys recently developed by CMU
      - Composition: (FeCo)-M-B-Cu where M=Zr and Hf



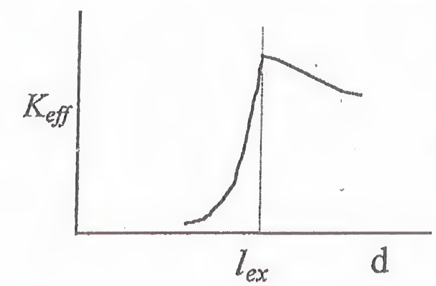
Soft Magnetic Materials

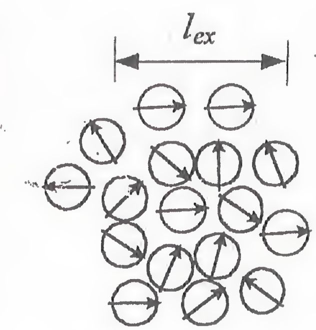
- **Nanocrystalline Vs. Nanocomposite Magnetic Alloys**
  – Nanocomposite Magnetic Alloys
    - Very high resistivity compared to nanocrystalline and polycrystalline alloys for well electrically insulated nanoparticles.
    - Fabrication process starts with a powder and compaction of powder into solid should permit fabrication of any size and shape of core just like for ferrites.



Soft Magnetic Materials

- **Major Challenge to Develop Nanocomposites**
  - Consolidation of the nanocomposite powder into a solid of almost 100% packing density without destroying the nanostructure of the particles.
  - Nanocomposites with good soft magnetic properties require the magnetic moments of neighboring particles be magnetically coupled
    - Known as "Magnetic Moment Exchange Coupling"
  - Critical distance within which the magnetic moments must be exchange coupled is the exchange coupling length
    - Coupling length <50 nm---requires full densification of the particle assembly
    - Coupling length different for each alloy





- **DIELECTRICS & CAPACITORS**

Dielectrics and Capacitors

- **Desired Properties of Dielectrics for Power Capacitors**
  - High Permittivity (High Dielectric Constant)
  - High Dielectric Strength
  - High Resistivity/Low Leakage Current
  - Low Dissipation Factor/Low Losses
  - Stable Characteristics under Temperature Cycling
  - Stable Characteristics at High Temperature (No Aging Effects)
  - Excellent Mechanical and Windability Properties

Dielectrics and Capacitors

Properties of Selected Dielectrics

Material	Dielectric Constant	Dielectric Strength (V/mil)
Air	1.0	75
Kraft paper (imp.)	4.0	2,000
Polymers	2.5-3.0	5,000-9,000
Mica	5.4-8.7	1,400
Glass	3.0-4.5	500
Tantalum Pentoxide	26	-
Aluminum Oxide	7.0	300
Ceramics	12-400,000	200-350

Dielectrics and Capacitors

- **Volumetric Efficiency Figure of Merit**
  - Volumetric Efficiency=Capacitance/Volume of Packaged Capacitor
  - For Capacitor Dielectric Only

$$\boxed{C/(Vol)_d = \varepsilon_o \varepsilon_r / t^2}$$

C = Capacitance (farad)
$(Vol)_d$ = Dielectric Volume (meter^3)
ε_o = Free Space Permittivity=8.85 X 10^{-12} farad/meter
ε_r = Relative Permittivity (Dimensionless)
t = Dielectric Thickness (meter)

Dielectrics and Capacitors

Volumetric Efficiency for Packaged Capacitors			
Type	Capacitance (μf)	Voltage (V)	$C/(Vol)_d$ μf/cm^3
Wet Tantalum	120	100	62
Solid Tantalum	10	100	8.9
Electrolytic	18,000	100	48
Polyester Film-Foil	3	100	0.22
Polyester Film-Foil	3	200	0.12
Metallized Polyester	10	100	1.6
COG/NPO	12	100	0.3
X7R	120	100	4.5
X7R	120	200	3.0
Z5U	720	100	18

Dielectrics and Capacitors

- **Energy Density Figure of Merit**
  - Energy Density = ½ CV^2/Volume of Packaged Capacitor
  - For Capacitor Dielectric Only

$$\boxed{\text{Energy Density} = \varepsilon_o \, \varepsilon_r \, (V/t)^2}$$

ε_o = Free Space Permittivity=8.8 X 10^{-12} (farad/meter)

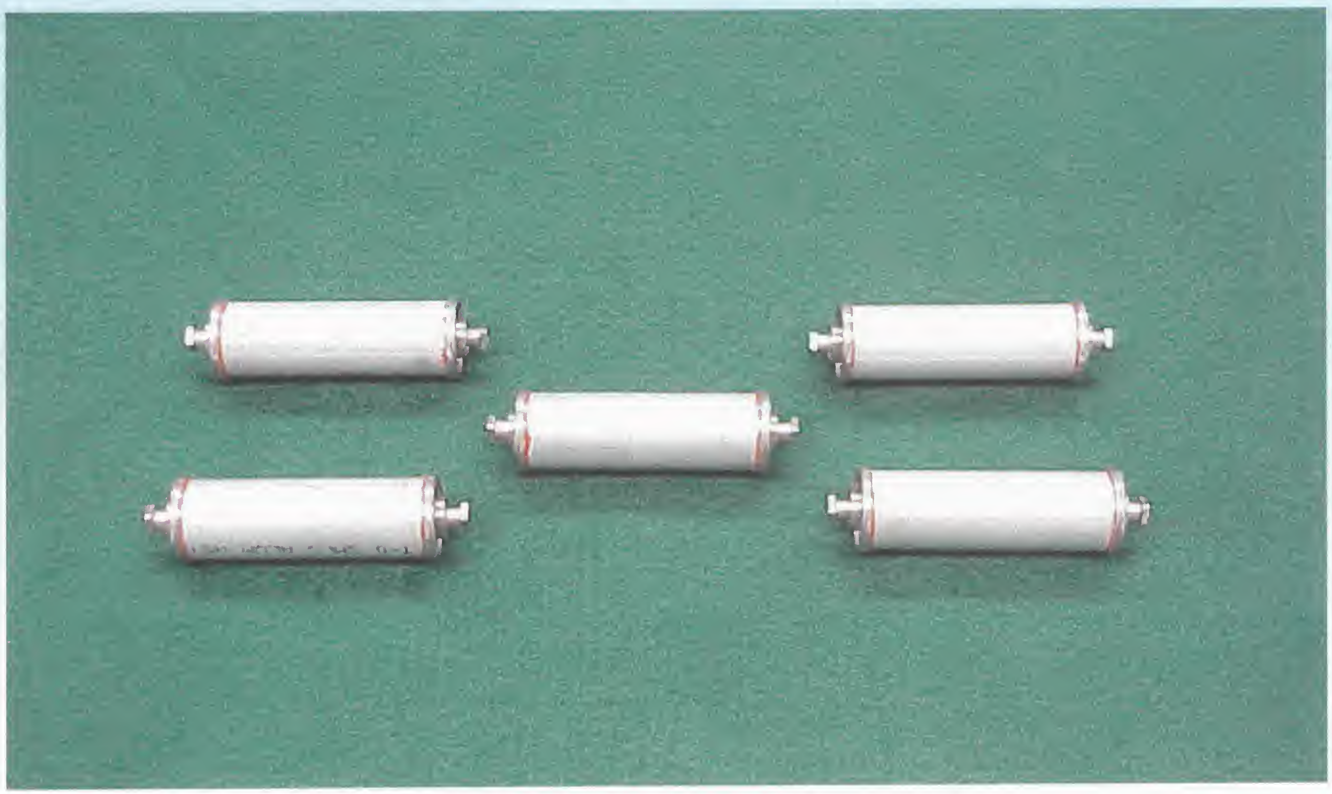
ε_r = Relative Permittivity (Dimensionless)

V = Charging Voltage (Volts)

t = Dielectric Thickness (meter)

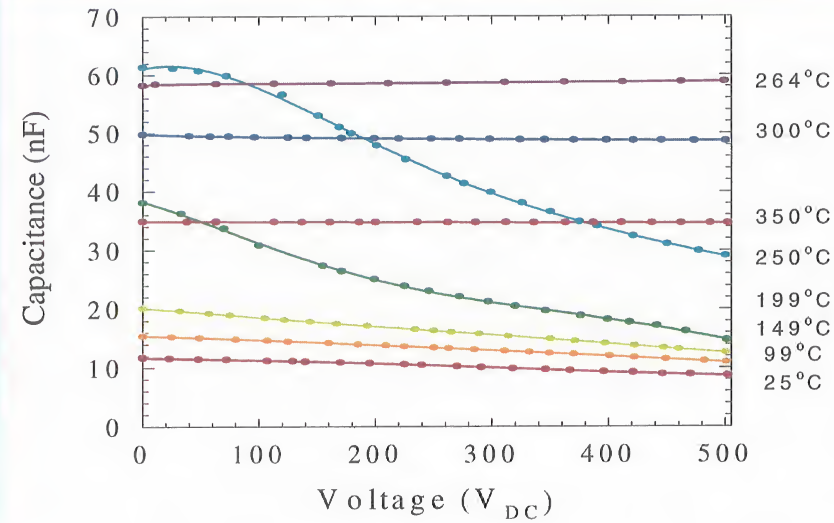
$(V/t)_{Max}$ = Dielectric Strength (Volts/meter)

17 uF, 250 VDC, Florene Poly Ester (FPE) Power Filter Capacitors

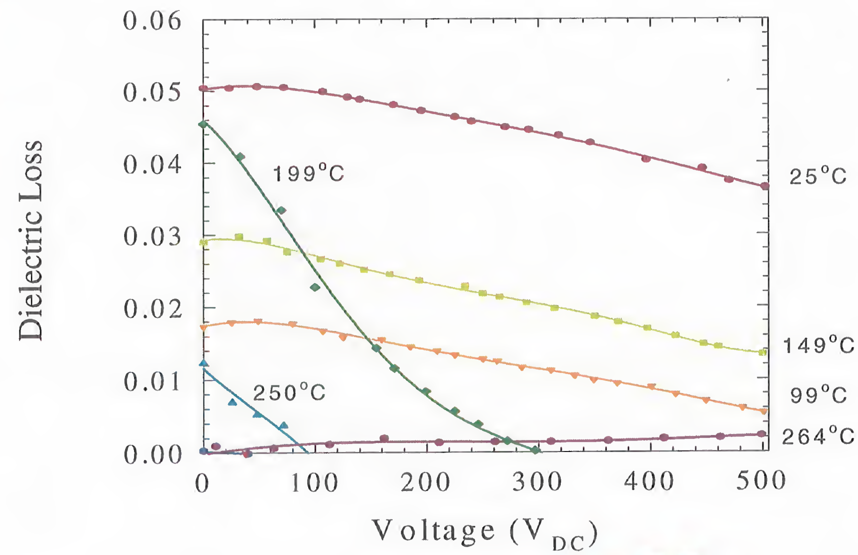


Dielectrics and Capacitors

- **High Temperature Relaxor Ferroelectric Multi-Layer Ceramic Capacitors (MLCCs)**
  - A new class of relaxor ferroelectric dielectric materials based on the recently discovered $BiMeO_3$-$PbTiO_3$ (Me=Sc, Yb, Fe, etc) family of morphotropic phase boundary containing perovskites being developed under SBIR contract.

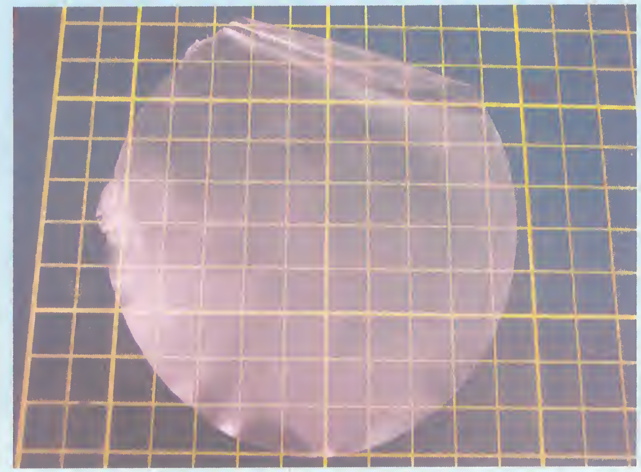


  - Phase I demonstrated MLCCs with volumetric efficiency > 1.4 uF/cm_3 and operating temperature to 300 C.
  - Voltage saturation measurements showed about a 2% change in capacitance over the voltage range of 0-500 V at 300 C.
  - Phase II selected for award and presently under contract with TRS Technologies.



Dielectrics and Capacitors

- **Nanocomposite Dielectric Capacitor Material**
  - A new class of high performance organic/inorganic capacitor films being developed under an SBIR contract .
    - Combines the advantage of inorganic materials (high dielectric constant) and organic polymers (high dielectric strength) to give high volumetric efficiency and high energy density.
    - Phase I completed using polypropylene as the organic material.
    - Phase I demonstrated a 25% increase in dielectric constant and 30% increase in dielectric strength compared to polypropylene to give an 85% increase in energy density and 25 % increase in volumetric efficiency.
    - Phase II selected for an award with emphasis on developing polypropylene with other additives and other high dielectric constant materials and also developing thinner films in order to increase the volumetric efficiency.



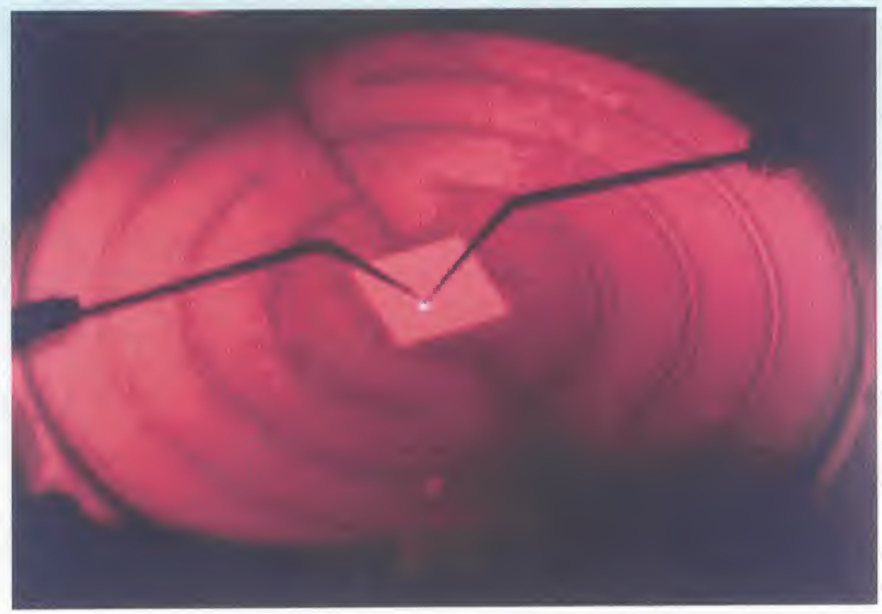
Organic/Inorganic Dielectric Capacitor Film Developed During Phase I

Test Capacitor Structure

- **WIDE BANDGAP SEMICONDUCTOR MATERIALS & DEVICES**

Wide Bandgap Semiconductor Materials

- **Objective**
  - Develop the Silicon Carbide (SiC) device material and fabrication technology (epigrowth, oxides, passivants, contacts) to enable the development of power devices which are
    - Very Reliable
    - High Temperature
    - High Off-State Voltage
    - Low On-State Voltage
    - High Current Density
    - High Frequency
    - High Radiation Resistance



Silicon Carbide Diode at 600 C

Wide Bandgap Semiconductor Materials

Advantages of SiC over Si

Property	4H-SiC*	Si*	Advantage
Energy Bandgap (eV)	3.26	1.12	Higher Temperature
Electric Field Breakdown (V/cm)	$2.2X10^6$	$2.5X10^5$	Higher Voltage Higher Current Density (Higher Dopant Levels)
Thermal Conductivity (W/cm K@RT)	3.0-3.8	1.5	Improved Heat Transfer

* Values from http://www.cree.com/products/sic/silicarb.htm

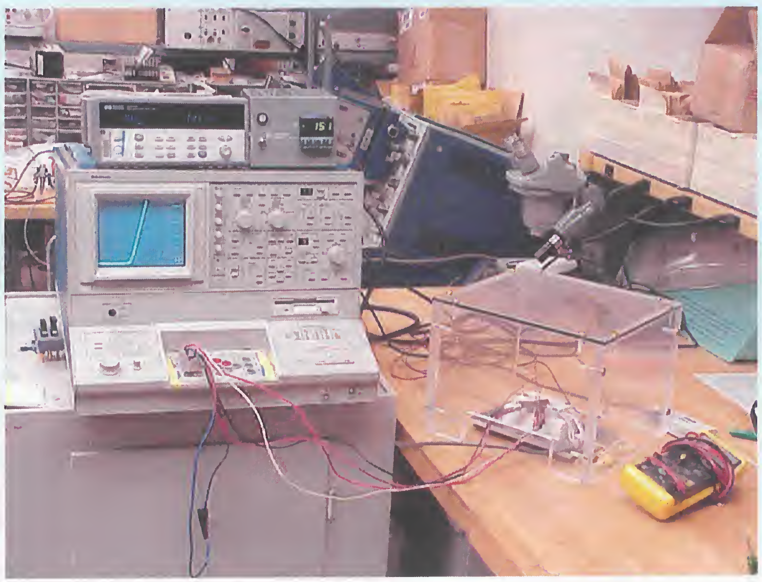
COMMERCIAL SiC DIODES

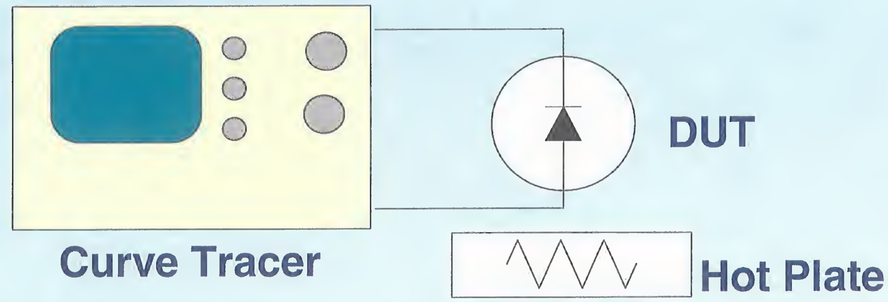
VENDOR	TYPE	SPEC SHEET	VOLTAGE (V)	CURRENT (A)
INFINEON (thin Q!)	SCHOTTKY	YES YES	300 600	10 4, 6, 12
MICROSEMI (Powermite)	SCHOTTKY	YES YES YES	200 400 600	1, 4 1, 4 1, 4
CREE (Zero Recovery Rectifier)	SCHOTTKY	YES YES	600 1200	1, 4, 6, 10, 20 5, 10
SOLID STATE DEVICES	SCHOTTKY	YES YES	300 600	40 5, 24

Silicon Carbide Schottky and Silicon PN Diodes Tested

SiC Schottky				Silicon pn			
Vendor	Part #	Voltage (V)	Current (A)	Vendor	Part #	Voltage (V)	Current (A)
Microsemi	UPSC 200	200	1	IR(Schottky)	10CTQ150	150	5
Infineon	SDT10S30	300	10	IXYS	DSEP8-03	300	10
Microsemi	UPSC 603	600	4	Microsemi	1N6628	600	4
Infineon	SDT06S60	600	6	IR	HFA08TB60	600	8
Cree	CSD 10060	600	10	IXYS	DSEI8-06A	600	8
Cree	CSD 20060	600	(Dual) 10	IXYS	DSEP9-06CR	600	9
Cree	CSD 10120	1200	(Dual) 5	IXYS	DSEP30-12A	1200	30

Steady State Test Setup



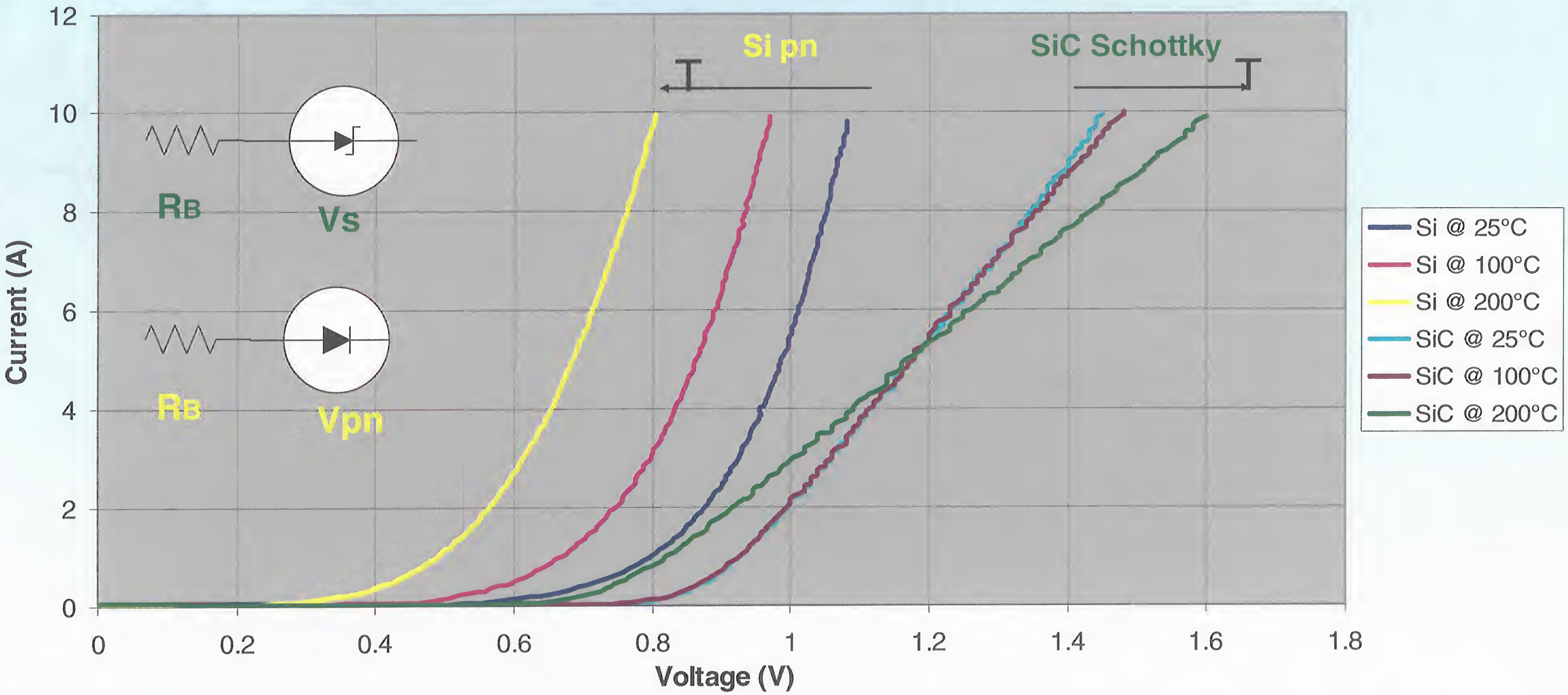


- Forward Characteristic Curve: Apply rated current and measure forward voltage (anode to cathode)
- Reverse Characteristic Curve: Apply rated reverse voltage (cathode to anode) and measure the leakage current

Temperature of the hot plate varied from 25C to 250C

Forward IV Characteristic Comparison

Si 300V 10A Ultra Fast pn (IXYS DSEP 8-03A)
SiC 300V 10A Schottky (Infineon SDT10S30)



•Difference between Schottky (majority, crossover) & PN (minority, no crossover)

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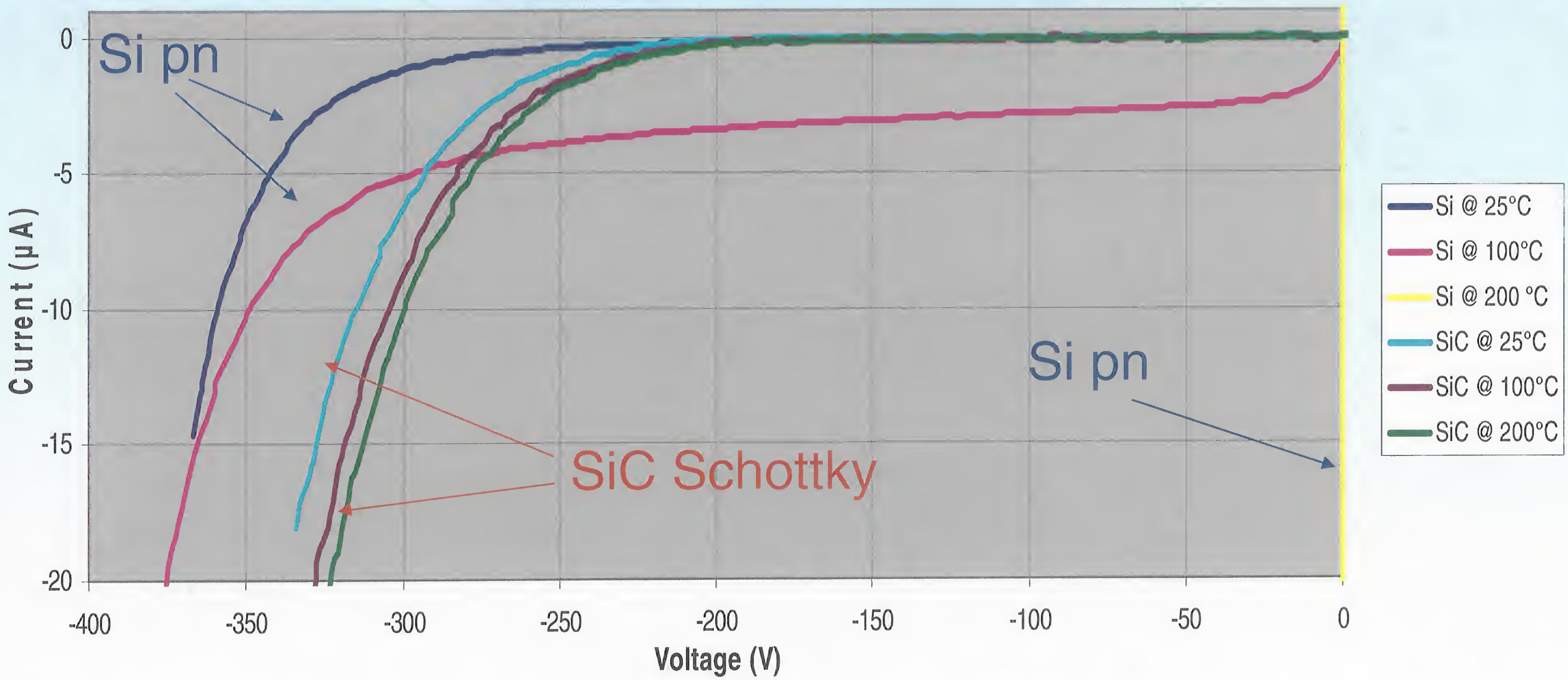
Reverse IV Characteristic Comparison

Si 300V 10A Ultra Fast pn (IXYS DSEP 8-03A)

SiC 300V 10A Schottky (Infineon SDT10S30)



- •Si PN: Lower forward voltage drop at 200C but no reverse voltage blocking capability
- •SiC Schottky: Larger energy bandgap (Eg) allows the device to block 300V at 200C

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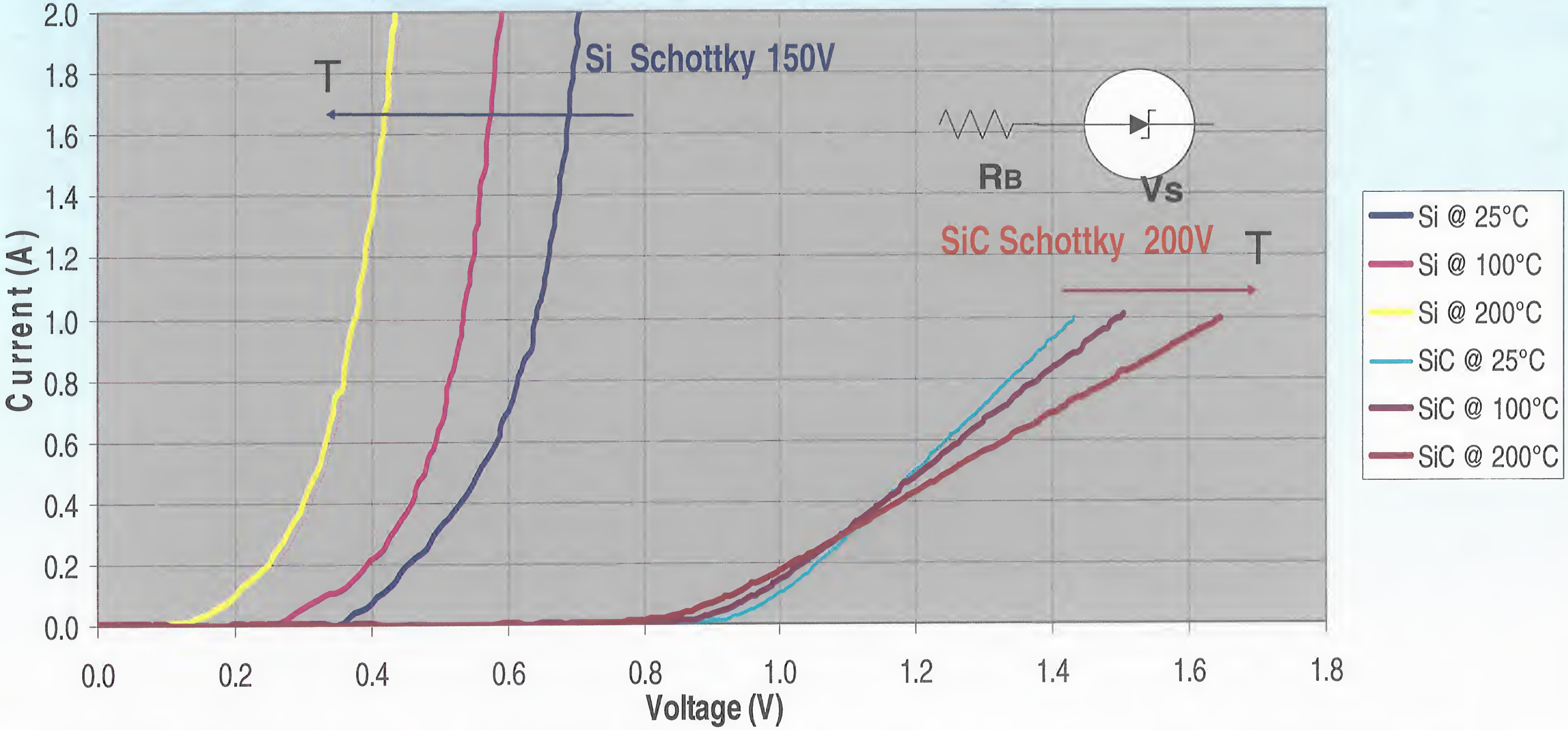
Forward IV Characteristic Comparison

Si 150V 5A Dual Schottky (International Recitifier 10CTQ150)

SiC Schottky 200V 1A (Microsemi UPSC200)



- Forward voltage for SiC Schottky is higher than for Si Schottky. SiC device voltage rating is higher than 200V (600V or higher)

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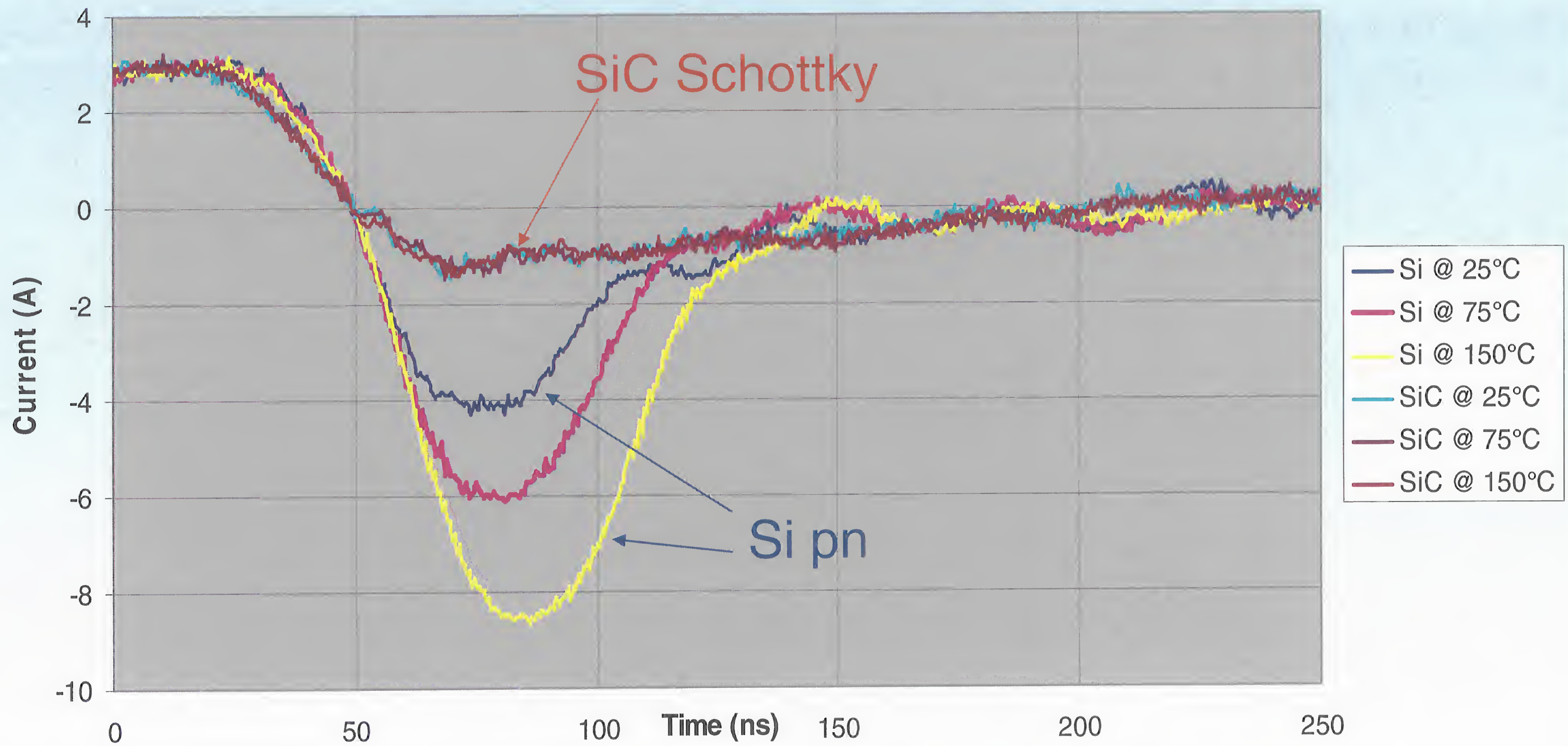
Transient Current Comparison in Buck Converter, $V_{IN} = 400V$

Si 600V 8A ultrafast pn (IXYS DSEI 8-06A)

SiC Schottky 600V 6A (Infineon SDT06S60)



- Si pn diode reverse recovery current increases significantly with temperature
- SiC Schottky diode transient reverse recovery current does not change with temperature

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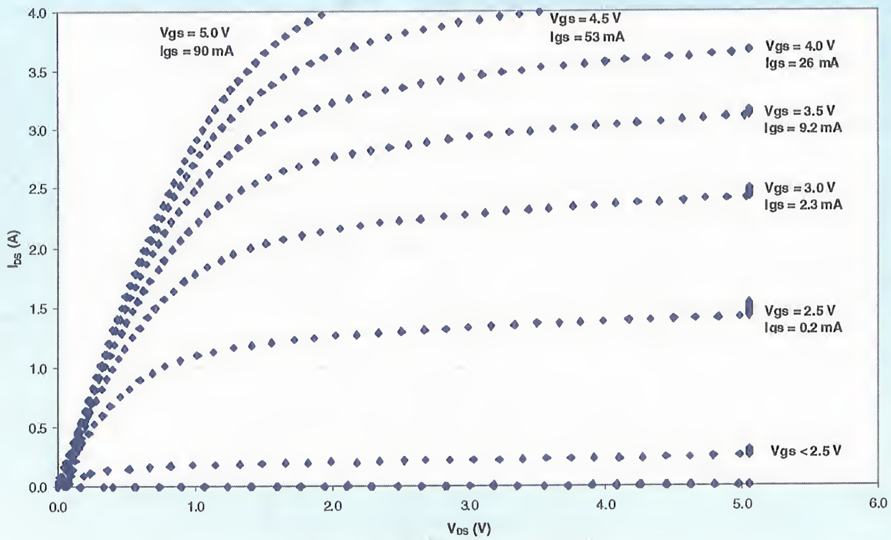
COMMERCIAL SiC SWITCHES

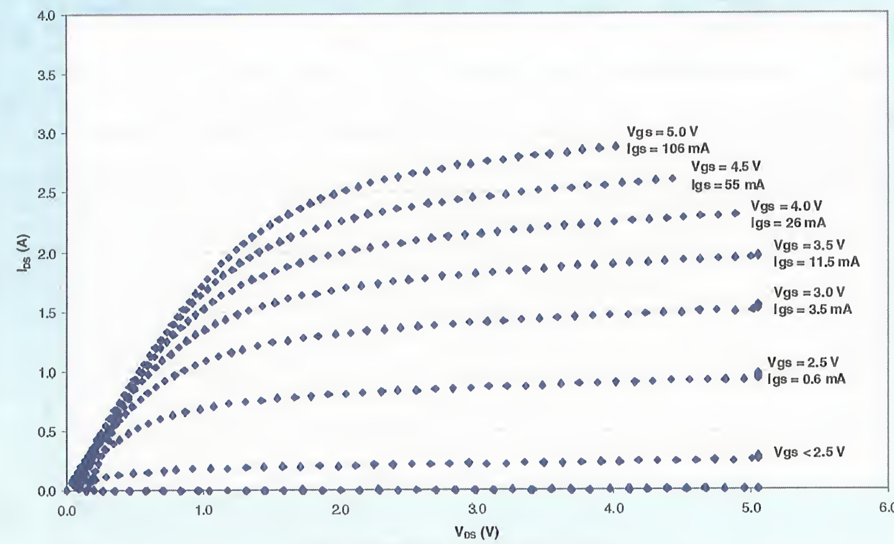
VENDOR	TYPE	SPEC SHEET	VOLTAGE (V)	CURRENT (A)

Normally-Off SIT's I-V Temperature Dependence

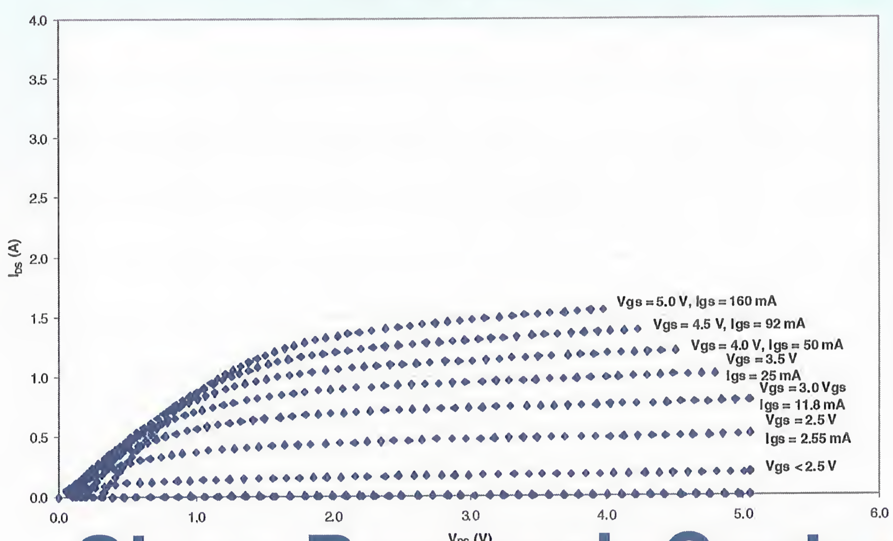
Drain-to-Source Characteristics at 25C
United SiC SIT 600V, 3A (N-2)



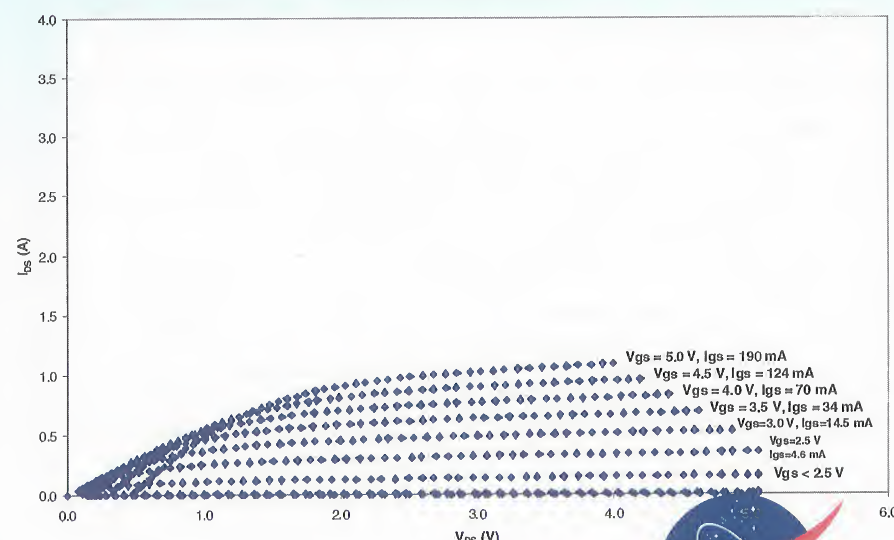
Drain-to-Source Characteristics at 75C
United SiC SIT 600V, 3A (N-2)



Drain-to-Source Characteristics at 150C
United SiC SIT 600V, 3A (N-2)

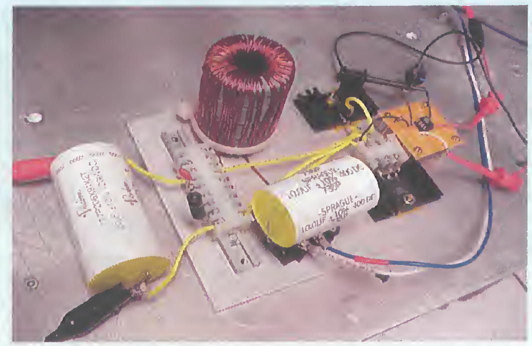


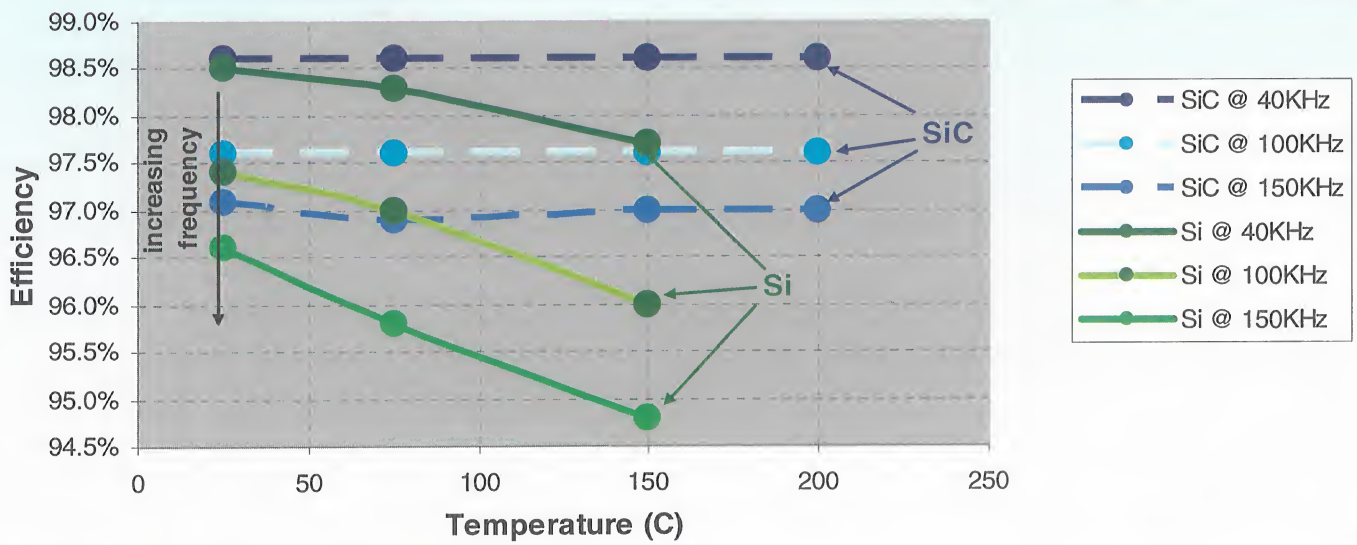
Drain-to-Source Characteristics at 200C
United SiC SIT 600V, 3A (N-2)



Efficiency Comparison of Si pn-junction and SiC Schottky Diodes in Buck Converter

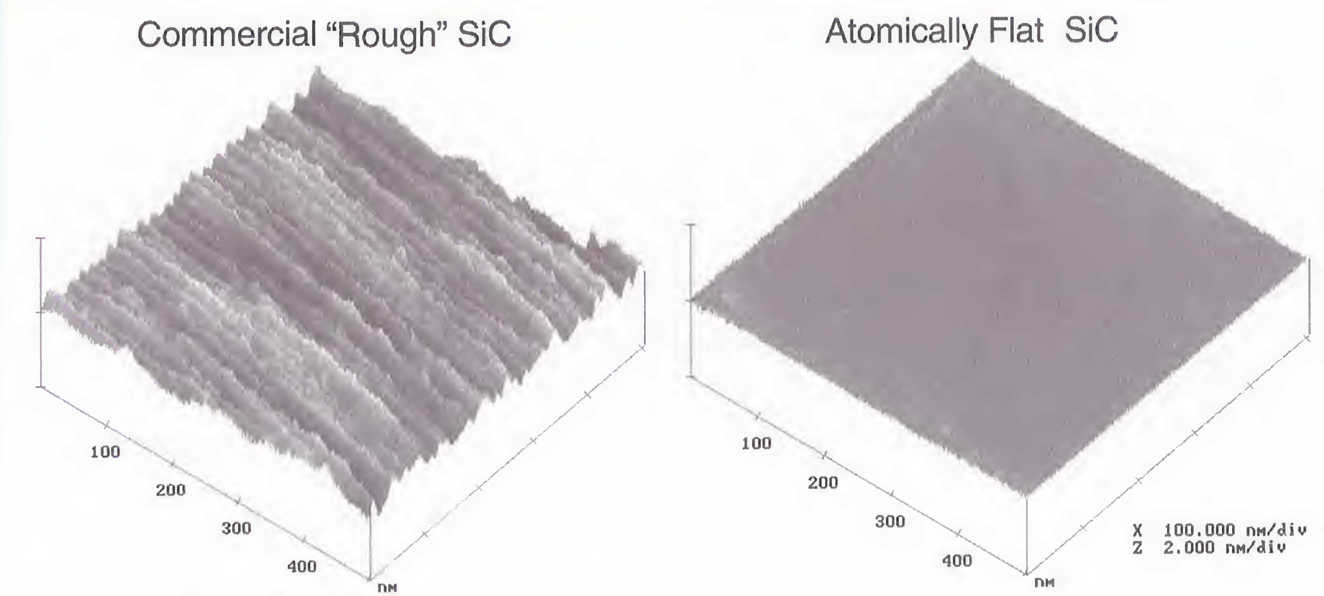
- Buck converter efficiency as a function of temperature and switching frequency using either the Infineon SDT06S60 (600V/6A) SiC Schottky diode or the IXYS DSEI 8-06A (600V/8A) ultra fast Si pn-junction diode.





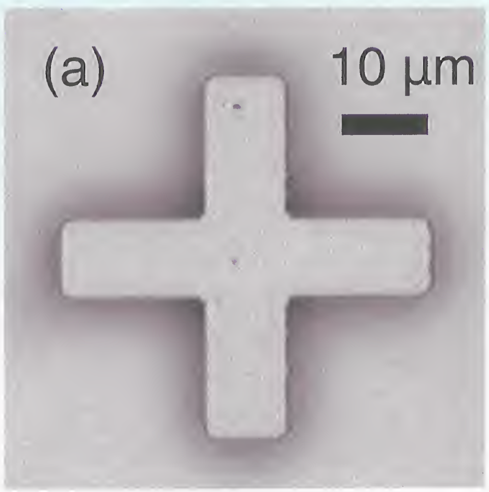
Wide Bandgap Semiconductor Materials

- **Sponsored SiC materials research with Sensors and Electronics Technology Branch at NASA Glenn**
  - New growth process called "Step-Free Surface Heteroepitaxy" under development to produce atomically smooth or flat 4H-and 6H-SiC substrates
    - Mesas with dimensions up to 200 μm square demonstrated on commercial 4H-SiC wafers
    - Mesas with dimensions up to 50 μm square demonstrated on commercial 6H-SiC wafers

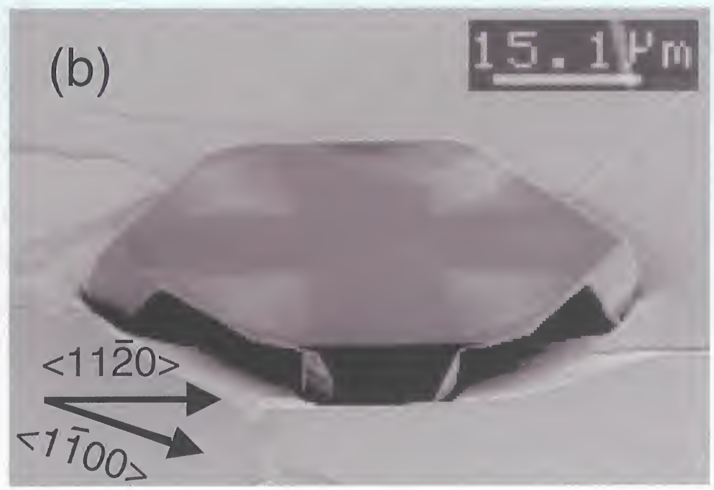


Wide Bandgap Semiconductor Materials

- **Sponsored SiC materials research with Sensors and Electronics Technology Branch at NASA Glenn**
  - Density of screw dislocations limits scale up of size and yield of step free mesas
  - New homoepitaxial lateral "web growth" process being developed to scale up size and yield of step free mesas
  - Webbed surfaces up to $4X10^{-3}$ cm^2 have been grown



Pre-growth optical photo of cross-shaped mesa



Post-growth SEM of "webbing" formed following 60-minute growth.

Wide Bandgap Semiconductor Materials

- **Sponsored SiC materials research with Sensors and Electronics Technology Branch at NASA Glenn**
  - Growth of defect free 3C-SiC on 4H-and 6H-SiC has been demonstrated using the new step free growth process.

Recipe “A”

Recipe “B”

3C-SiC layer grown on 0.2 mm x 0.2 mm screw dislocation free mesa on following oxidation to reveal step free defects.

Conclusions

Component	Technology Improvements Needed
• Transformers and Inductors	• High frequency, high temperature, low core loss soft magnetic materials • High temperature wire insulation , interlayer insulation, and terminations
• Capacitors	• High temperature, low loss, high dielectric constant, high dielectric strength dielectrics • High temperature terminations
• Switches and Diodes	• High quality SiC substrates, oxides, and passivants for higher voltage and current devices • High temperature contacts • High temperature packages

Long Term Temperature Aging and Stability Data Needed for All Power Electronics Components.